

Articles

Incorporation of Bioinformatics Exercises into the Undergraduate Biochemistry Curriculum

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The field of bioinformatics is developing faster than most biochemistry textbooks can adapt. Supplementing the undergraduate biochemistry curriculum with data-mining exercises is an ideal way to expose the students to the common databases and tools that take advantage of this vast repository of biochemical information. An integrated collection of exercises based on pet proteins has been assembled. The exercises described are applicable to either a lecture or laboratory format and require only basic desktop computers, an Internet connection, a current web browser, and the free Chime plug-in module. In an open-ended, inquiry-based format, the assignments ask students to explore concepts such as the relative information content of the different biopolymers, the relationship between primary sequence and tertiary structure, and how sequence conservation can be used to find an enzyme active site.

Keywords: Bioinformatics, data mining, molecular visualization.

The field of bioinformatics is rapidly changing the way biochemists conduct research [1]. No longer is it an arduous task to identify a gene. That which took years to do in the past often can be done in a matter of weeks or months using powerful computational algorithms and vast databases of genomic sequence information. One of the primary goals of bioinformatics as a field is to provide tools that allow scientists to find and correlate data from across disciplines, providing connectivity between different types of information (Fig. 1). If one analyzes the traditional biochemistry curriculum, one finds that many of the data types that form the foundation of bioinformatics are already discussed in these courses, but in a segregated and less integrated manner. By incorporating bioinformatics into the undergraduate biochemistry curriculum, the interrelationships between these subjects become more evident to the students.

The bioinformatics databases, and the research tools necessary to access them, are used extensively by biochemists at all levels. It is, therefore, just as essential to teach students the tools of data mining, sequence analysis, and molecular visualization as gel electrophoresis and enzyme kinetics. In addition to being powerful research tools, bioinformatics provides a terrific pedagogical opportunity to illustrate the enormous data content in even relatively short protein or nucleic acid sequences. For instance, students can readily discover the clustering of evolutionarily conserved sequences in the active site by performing a multiple sequence alignment

(MSA).¹ Because these tools are generally freely available via the Internet, their incorporation into the curriculum does not require a capital investment in the form of expensive software packages and simply requires the instructor to provide some guidance and a web site with the appropriate hyperlinks. The exercises described below promote active inquiry within the curriculum and hopefully a better understanding of the underlying biochemistry. At the same time, the students become much more comfortable with the use of computers and the Internet as academic tools.

Because of the rapid nature of these changes, biochemistry textbooks have not kept pace with the developments in bioinformatics. It is, therefore, necessary to provide supplemental exercises that actively engage the students and allow them to explore the realm of computational biology within the biochemistry curriculum. A single lecture or discussion on bioinformatics and the genome projects at the beginning of the course generally provides sufficient context for the students to begin the exercises described herein. Other authors have highlighted the contents of the various databases used as part of these activities, and they are not described in detail here [2–4]. Instead, the focus will be on a detailed discussion of how these tools can be integrated into an undergraduate biochemistry course through a series of problem set assignments. We have used these exercises in both one- and two-term introductory biochemistry lecture courses. A recent report by Scott Cooper [5] describes the implementation of related exercises into the laboratory setting. The URLs for the sites used during these exercises are listed in Table I.

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¹ The abbreviations used are: MSA, multiple sequence analysis; 3D, three-dimensional; PAH, phenylalanine hydroxylase.

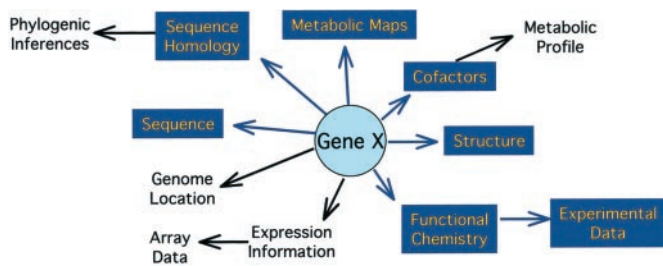


FIG. 1. **Overlap between bioinformatics and the topics commonly taught in introductory biochemistry.** Arrows indicate the cross-referencing of information common in the bioinformatics databases. Topics on *dark backgrounds* are those already covered in the majority of introductory biochemistry courses and textbooks. Adapted from Ref. 1.

Direct links should be provided on a course web page every term, however, to avoid problems associated with periodic changes of these addresses. It is also essential that suitable workstations are available for student use, especially in cases where home network connections are either slow or unreliable.

When used in the lecture course, the exercises are generally parsed out over the full semester. Fig. 2 provides an overview of the exercises such that one major bioinformatics task is incorporated into each problem set (five in total usually). In this way, the computational assignments parallel the course content as much as possible. To prevent students from focusing excessively on the use of the computer rather than the analysis of the output, each exercise begins with detailed instructions that lead the students through the manipulations and mouse clicks. These instructions also describe the expected output and common mistakes, including the error messages they might generate inadvertently. As the students become accustomed to working on these web sites, the instructions become less detailed and more task-oriented. In this way, students gain independence and self-confidence in their ability to find the necessary information on their own. Toward the end of the semester, an independent assignment (usually for extra credit) is provided based on a recent report found in the popular literature. This assignment assesses simultaneously the student's ability to independently navigate these sites without being told where to obtain the necessary data and demonstrates how far their data-mining skills have advanced during the term.

GOALS

The goal of these exercises is to introduce junior/senior level undergraduates to some of the common computational tools used by biochemists. These tools are primarily Internet-based. They require basic Internet access and a web browser such as Netscape. One site used extensively for molecular visualization, Protein Explorer [6–8], is currently not compatible with Internet Explorer, although newer versions may fix this conflict. Also required is the plug-in module Chime, available free from MDL at their web site (Table I). Upon completion of these exercises, the students should be able to carry out simple BLAST searches, multiple sequence alignments using ClustalW, and basic handling of structural data including accessing, viewing, and on-screen manipulation of macromolecules.

TABLE I
Internet addresses (URLs) for the primary web sites used in these exercises

Course web sites that use these exercises
C483 (Indiana University): chemlearn.chem.indiana.edu/c483/
C484 (Indiana University): chemlearn.chem.indiana.edu/c484/
Bioinformatics sites important for these exercises
BLAST: www.ncbi.nlm.nih.gov/blast/
BRENDA: www.brenda.uni-koeln.de/
ConSurf: bioinfo.tau.ac.il/ConSurf/
ExPASy: www.expasy.ch/
IUBMB Nomenclature: www.chem.qmw.ac.uk/iubmb/enzyme/
KEGG: www.genome.ad.jp/kegg/kegg2.html
MSA: npsa-pbil.ibcp.fr/cgi-bin/npsa_automat.pl?page=npsa_clustalw.html
OMIM: www.ncbi.nlm.nih.gov/Omim/
PDB: www.rcsb.org/pdb/
Protein Explorer: proteinexplorer.org/
PubMed: www.pubmed.gov
Free software downloaded for use in these exercises
CHIME: www.mdlichime.com
CN3D: www.ncbi.nlm.nih.gov/Structure/CN3D/cn3dinstall.shtml
Shockwave: sdc.shockwave.com/shockwave/download/frameset.fhtml
VRML: www.karmanaut.com/cosmo/player/
Structure tutorials available on-line
C483/C484 Tutorial: www.indiana.edu/~c484/pdf_files/Unknownns.pdf
PE Quick Tour: molvis.sdsc.edu/protexpl/qtour.htm
CMU Chime Tutorial: info.bio.cmu.edu/courses/03231//chime_tut/chime.html

The students also gain familiarity with common databases that cross-index many pertinent facts about proteins, enzymes, and nucleic acid sequences including links to tabulated enzyme kinetics data and metabolic maps. Links to structural classification and conserved domain families, as well as the cross-references to metabolic diseases resulting from abnormalities in specific proteins, can be explored.

CLASSROOM/LABORATORY EXERCISES

Getting Started

Each student receives an unknown protein at the start of the semester in the form of two peptide sequences (Table II). The assumption is that the students have obtained a small amount of this protein that was subjected to mass spectrometric analysis after an enzymatic digestion yielding the observed sequence fragments. The protein unknowns were selected based on enzymes the students will encounter during the course, and practically all of them can be found in the index of common undergraduate textbooks. Therefore, once the protein is identified, any student who wishes can easily read some background material on it. The proteins represented by the peptides in Table II have been predominantly taken from *Escherichia coli*, the exceptions being some common proteins not found in prokaryotes, in which case human proteins have been used. For various reasons, the students will not always return with the *E. coli* form of the protein, but they invariably find the correct enzyme.

Project 1: Identifying an Unknown Protein—The first objective is to identify their unknown enzyme by performing a BLAST (basic local alignment search tool) search against a collection of non-redundant protein databases [9, 10]. There are several portals available for these types of

searches, but the NCBI web page is the resource we have used. This site was chosen because of the extensive documentation available if the students care to read more about the process. Instructions lead the students through the task of inputting a single peptide into the search. The

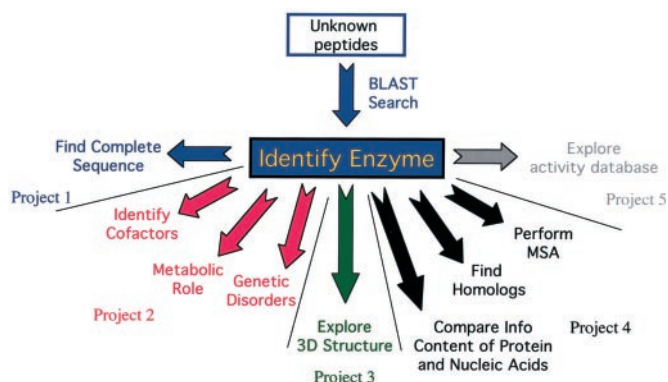


FIG. 2. Schematic overview of the bioinformatics exercises and their division into five general projects performed over the course of the semester.

students eventually perform five BLAST searches. The first two use each of the peptides alone. The third and fourth searches use both peptides but vary the order in which they are entered. Finally, for the fifth BLAST search, the students enter one of the peptides backwards (C → N) and attempt to find the parent protein. Successful identification of all unknowns can be obtained by using the default search settings. Students are asked to find the meaning of the expectation value (E-value) in the documentation before they analyze the output from these searches. Searching against both peptide fragments provides E-values of $\approx 5 \times 10^{-4}$ or better (lower) for each protein listed in Table II. The students are pointed to the alignment portion of the output that can be observed if they scroll down their browser window for further comparison of their query with the retrieved sequences. Finally, many students need to be informed about database accession numbers and the enzyme classification system, because these identifiers are the easiest way for them to proceed through the additional assignments on later problem sets.

Once the students have run the BLAST searches and

TABLE II
Tryptic fragments of common metabolic enzymes for use as unknowns

An annotated list of the enzymes to which these unknowns correspond can be obtained by sending E-mail to the corresponding author. To accommodate classes with larger enrollments, the fragments listed in this table can be duplicated and given a unique sequence identification number (see class web page for an example). Each student receives a unique sequence number for their unknown and hence believe they have a different protein from other students in the class.

No.	Peptide 1	Peptide 2
1	DVQFGLATMCIGLGGIATVFER	INLNGGAIALGHPLGCSGAR
2	ATIANSPEYGATCGFFPIDAVTLDYMR	WQDGNSTVEEDIHALAGWLK
3	DRPMAVNGQVEILPMMYLALSVDHR	QQASLEEQNDALSPAIR
4	NIFSVIYDGTQPNPTTENVAGLK	AVTMIAENLPLAVEDGSNAK
5	AGSVFVNNYNDGDMTVPFGGYK	VYGEVATTSHELAMIVR
6	HNLPHNSLNFVHGGSGSTAQEIK	ENNFALPAVNCVGTDSINAVLETAAK
7 ^a	MDPPCTNTTAASTYLNPNYVR	FYATNDTEVAQSNFEALQDFFR
8 ^b	TVGWIAHWSEMHSDDGMK	AMGIPSSMFTVIFAMAR
9	FQTAFQAQLADNLQSALEPILADK	ADAPLIQWDATSATLK
10	AYFTSATMIIAIPITGVK	DIGTLYLLFGAWAGVLGTALSLLIR
11	SGETEDATIADLAVGTAAGQIK	GMPLYEHIAELNGTPGK
12	QHEFSHATGELTALLSAIK	LLYECNPMFLAEQAGGK
13	MDSYVDQLQAQGGSMIMLAK	YYDELPTEGNEHGQAFR
14	QGLQLGFSSFPCHQGTGLDR	QGLSGQSLPLGFTFSFPCR
15	NHLNMHFVSNVDGTHIAEVLK	AVGEFGDITANMFEFWDWVGGR
16	EIQVAGSLEALNELDLDR	EQHVTIPAHQVNAEFFEFGK
17	YAGQDIVSNASCTTNCPLAPLAK	WDEVGVVDVVAEATGLFLTDETAR
18	VDGGAVANNFLMQFQSDILGTR	IPISGIAGDQQAALFGQLCVK
19	STQVYQDQVWLPAAETLDDLIR	FPEHCIGIGIKPCSEEGTK
20	GYTSWAIGLSVADLAESIMK	ITVVGVGAVGMACAISILMK
21 ^a	TPGAVNACHLSCSALLQDNIADAVACAK	GISLANWMCLAK
22	VAVLGAAGGIGQALALLK	ACIGIITNPVNTTVAIAAEVLK
23 ^b	ATLLIETLPAVFMDEILHALR	EQDAPITADQLLAPCDGER
24 ^c	AFSQFLNLANLTAEQYHSISPK	AVESLSLELVLTAPTEITR
25	FANQILSYGAELDADHPGFK	ILADSINSEIGILCSALQK
26	HSFNPHILAIQAIAEER	AGLTLGVDPGGSGIEYWK
27	IAAVAEDGEPVCTYIGADGAGHYVK	AGAGTDAADISLKPFLDK
28	ISYISTGGGAFLEFVEGK	YAALCDVFMVDAFGTAHR
29 ^c	EEGYSFDFAYTSVLK	AIHTLWNVLDELQAWLPVEK
30 ^c	EQGLNSENFVAFNLTER	GVLTNLGAVAVDTGIFTGR
31 ^c	DLPEDIYVVIIEIPANADPIK	FMSTAMFYPCNYGYINHLS LDGDPVDVLVPTPYPLQPGSVIR
32 ^c	VILFIGDGSLLQTLVQEIISTMIR	MIEVMLPVFDAPQNLVEQAK
33 ^c	DVNVPDIGSDEVEVTEILVK	EVNVPDIGGDEVEVTEVMVK
34 ^c	QDLIFGCEQGVDFVAASFIR	GDLGVEIPVEEVIFAQK
35 ^c	TGFHMLHTLFTSLQFPQIQR	AATAGNGNEAAIEAQAGVEQR

^a This unknown has no KEGG entry.

^b This unknown lacks an OMIM entry.

^c This unknown has an OMIM entry but is not hyperlinked appropriately from KEGG.

identified their protein, they are asked to compare the output from the different searches. In several of the cases, searching on just one of the two tryptic fragments provides an error that no significant hits were obtained. Many of our students find the concept of probability confusing, especially the idea that given a database the size of the human genome, one expects to find a perfect or near match for short random amino acid sequences. The students see clearly how adding additional sequence information improves the statistics of the sequence match. They learn about the length of sequence required to get unambiguous hits and the importance of gap penalties. It is extremely useful for the students to talk with one another about these issues, as the outcome varies depending on the length and complexity of the short peptide fragments assigned.

Several errors appear every time this exercise is assigned. The most common occurs when the student accidentally performs a BLASTn rather than a BLASTp search, the result being an error (Warning: BLAST: No valid letters to be indexed) with no additional output. Whereas the newest version of the NCBI BLAST web page separates the nucleic acid and protein search links, students still manage to perform their searches incorrectly at times. The other source of confusion derives from multiple hits to what appear to be the same protein. Even non-redundant databases contain overlap because of multiple entries and partial gene sequences. The students must look at the pairwise alignments and make a judgment regarding the correct identity of the target protein. In certain cases, one of the fragments comes from a highly conserved region of the enzyme and thus appears to be identical to the protein from several organisms; the students must rely on the searches that employ both fragments to distinguish the most likely species from which their protein derived. Listed below are examples of some open-ended questions that we use to promote student reflection on this exercise.

- What is the name of your unknown protein, and from what organism was it isolated (if you can tell)?
- Why are there multiple hits in the output for what appears to be the same enzyme?
- When you entered your peptide in backwards, did you get a significant match to anything in the database? What does this result imply about the importance of directionality and orientation in biological macromolecules?
- Compare the results from the two searches that used both peptide fragments. Did you get identical results? Why, or why not? What aspect(s) of the BLAST search parameters influence(s) these outputs? Hint: find the peptide fragments from within the full amino acid sequence of the protein, and think about how the computer will try to find these fragments during the search.
- How might you use a BLAST search for something other than identifying a protein for which you have partial sequence information?

Project 2: Using the ExPASy (Expert Protein Analysis System) and On-line Metabolic Maps—The second phase of the project involves finding additional information about the unknown enzyme now that it has been identified. If the goal were simply to obtain the full sequence of the protein,

the students could use the direct links to the GenBank™ entries from the BLAST output to obtain this information. The ExPASy web pages have a lot of additional information on each protein, and it is therefore useful to direct the students toward this resource. The students can find the enzyme on ExPASy by one of several methods. The formatted BLAST results contain the accession number for each sequence, as well as the enzyme classification number and the name of each hit. Any one of these pieces of information can be used to trace back to the full protein sequence. In the case of the E.C. number or enzyme name, the students arrive at the NiceZyme page and must then select an organism for which they wish to proceed. In this way, the student might identify a homolog of the actual protein. The NiceZyme display has a lot of useful information about these proteins, and the students are asked to identify key features about their protein, in addition to finding their peptides within the intact protein sequence. By using the accession number, the students arrive directly at the NiceProt page, which has more detailed and specific information on the exact protein. Students are asked to compare the types of information available on the NiceZyme and NiceProt pages, because the links to certain types of information differ. The students are also given a laundry list of biochemical characteristics that they must find through their investigation of these pages. It is often advantageous for pairs or small groups of students to compare the findings from their respective unknown proteins. Not all enzymes use cofactors, for instance, but the breadth of available information becomes evident upon looking at several examples.

After exploring ExPASy, the students are directed to the on-line metabolic pathway maps. The links through ExPASy take the students to the traditional Boehringer-Mannheim metabolic map. Although quite complete, this pathway map suffers from the daunting complexity of its paper counterpart, inciting a fearful response from the students. The set of hyper-linked pathway maps available from KEGG (Kyoto Encyclopedia of Genes and Genomes) provides a much more pedagogically friendly environment. A caveat relevant to this exercise is that a few common proteins one might consider as potential unknowns do not appear on the metabolic pathway maps. For instance, lysozyme, trypsin, and carboxypeptidase are all missing from the KEGG database. These proteins otherwise make excellent unknowns for these assignments. During two semesters, lysozyme and carboxypeptidase have been included within the exercise to illustrate the point that databases have biases and may have significant omissions as a result. In both interactions, the students were forewarned that two of the unknown proteins would not appear in KEGG. The students with these unknowns were instructed to describe the physiological role of these enzymes in lieu of the normal discussion of the metabolic pathway. Each instructor should decide whether to include these sequences when assigning unknowns to their students. They are appropriately annotated in Table II.

Once the students find their protein within the metabolic pathways, they can also obtain extensive information about the enzyme on KEGG. The hyperlinks within the maps allow them to easily overlay the contents of other

databases upon the metabolic pathway. In particular, we use the superposition of PDB and OMIM (On-line Mendelian Inheritance in Man) databases. The latter database catalogs inheritable diseases because of inborn genetic errors [11]. In this way, students with interest in medicine can determine whether their unknown protein has been linked to a genetic disorder. This portion of the exercise is sometimes problematic for the students as the links between KEGG and OMIM are incomplete. Only two of the unknown enzymes lack OMIM entries (Table II). Eight others, however, have OMIM entries, but KEGG fails to provide an appropriate connection. Students can be instructed to search OMIM directly (link provided in Table I) or told to explore the enzyme phenylalanine hydroxylase (PAH) in the event that they cannot find a metabolic deficiency related to their unknown enzyme.

As part of this assignment, the students are asked to perform a treasure hunt and obtain various pieces of information about their enzyme. This project familiarizes them with the types of data collected in these entries so that they can return to these sites later in the semester to find related information for future assignments. They are encouraged to explore beyond the realm of the exercises and experiment with the bioinformatics tools available through these sites.

Project 3: Finding, Manipulating, and Understanding 3D Structure at the PDB Web Site—The unknown enzymes selected for inclusion as part of these projects have all been characterized crystallographically. This criterion was imposed to facilitate using the same set of enzymes for every step of the process. In certain instances, the structure was solved from a different organism, so the students must be made aware that the sequence may not match exactly with the one they identified as part of Project 2.

The first phase of this project requires the student to use a tutorial to learn how to access the PDB, find a structure, and view it by using PE (Protein Explorer) and Chime [8]. There are a variety of ways to teach the students how to use these programs, depending on the students' familiarity with computers, as well as the time available either in or out of class to learn the required commands. Instructors wishing to familiarize their students with these programs do not need to write their own tutorial. Rather, they may be better off using one already prepared or adapting one of those to suit their particular needs. An excellent and detailed PE tutorial is available on the PE web site to teach students the full gamut of structural manipulations available within the program. We found this exercise to be too much for some of our undergraduates having their first exposure to molecular visualization. A shorter QuickTour of PE was developed recently and can be used to familiarize students with the most common PE commands. Concurrently, we developed a similar short tutorial that acquaints the students with the content of the PE windows and the embedded Chime menu commands. The first page of the tutorial introduces the students to the three windows and the QuickViews menu. This user-friendly option allows the students to perform simple tasks, such as zooming, with a click of a button. We chose to also teach the students the mouse actions that zoom, rotate, and translate the molecule, because the latter com-

mands are essential for use of Chime independent of PE. Knowledge of these commands enables the students to manipulate structures at other web sites that only contain embedded Chime structures. The remainder of the tutorial walks the student through the structure of a small protein such as protein G. Students prefer to start with a short polypeptide with simple topology, because they can see the secondary structure, as well as specific amino acids, without extensive manipulation of the structure. Initially, the students are guided through the structure with detailed instructions on how to select residues, color them, and display them in a various representations. Students then learn to obtain distance measurement and other data through manipulations of the structure with the mouse. Last, students are made aware of command syntax required to manipulate structures containing multiple polypeptide chains and non-proteinaceous ligands.

Once the students have become familiar with the simple commands, they proceed to an analysis of their unknown protein. They are instructed to find the structure of their protein in the PDB using the "Search the Archive" feature from the PDB home page and the name of the protein. Because the PDB search sometimes yields a large number of structures, the students should be advised to choose a structure with a bound substrate or inhibitor, if available, as such structures facilitate the localization of the active site. They are also advised to pick the structure with the most complete polypeptide sequence rather than a small fragment. In reality, however, it makes little difference which structure they choose. Practically any PDB file can be used to develop the skills necessary to view, manipulate, and understand protein structure. Once the structure has been selected, the student must view the model in space-filling and cartoon modes and provide a print out of each model after some minor manipulations. The latter exercise serves two purposes; it shows the grader that the student has (a) found the correct model, and (b) learned to use PE to manipulate the on-screen image of the structure. Most students are able to complete these tasks with little difficulty.

Although these exercises allow assessment of the student's mastery of PE, they do not provide information on the student's ability to use their acquired structure manipulation skills to understand macromolecular models. These skills are assessed with a writing assignment in which the student describes the juxtaposition of secondary structure elements in their assigned protein, as well as any other structural features they find interesting. An example description is provided on the class web page to help students formulate their own paragraph. In addition to the prose description, they are instructed to include a sketch of the topology and a detailed figure generated in PE that illustrates one of their points, such as a close-up view of a ligand binding interaction.

Most of our students find this task extremely challenging. Introductory biochemistry texts often contain fabulous graphics of protein structures these days, but the students often see these images simply as pretty pictures. They make little attempt to understand these structures at a deeper level. Hence, when confronted with their protein, they have a hard time selecting a place to start their

investigation. Furthermore, they cannot deconstruct the architecture. Getting students to let go of their bias toward organizing their discussion based on the primary structure is particularly difficult. The process of transferring their visual cues into a coherent description, however, teaches them how to examine and understand the complexities of biomolecular structures.

To help the students improve their scientific writing skills, the short descriptions are evaluated and returned with extensive comments. The students are then encouraged to resubmit their paragraphs after making the appropriate revisions. For many students, the initial exercise of writing about their unknown protein is insufficient to raise them to a deeper level of understanding regarding protein structure. Our experiences indicate that the revision process actually leads to the most significant conceptual development.

Project 4: Multiple Sequence Alignments and Sequence Conservation—A number of current biochemistry textbooks incorporate MSA and phylogenetic trees to illustrate certain simple evolutionary concepts. It is not always clear to the students, however, that these types of sequence comparisons can be performed on practically any protein and used to discern a lot more than the evolutionary date at which two species diverged from one another. The MSA can be used for a variety of biochemical pursuits. For instance, one can find relationships between seemingly disparate enzymes or show how a seemingly random pattern of primary sequence conservation clusters in three-dimensional space in the active site or key regulatory sites of enzymes. This assignment lets the students identify the position of conserved residues in the 3D structure and discover that conserved residues tend to cluster together when viewed in three dimensions.

The students are asked to align the sequences of their unknown protein from five or six different organisms. They obtain FASTA-formatted sequences from the EXPASy site via the NiceZyme page they have visited previously. Included among these sequences should be that of the structure they found in the PDB. As the sequences are gathered, they can copy them into a Microsoft Word document or other text editor so that the file can be transferred electronically and not retyped for submission into ClustalW. The student can then access the ClustalW program [12] at any number of different web sites, including the EBI or PBIL. For the purposes of this exercise, default alignment parameters have been quite successful. The qualities of the alignments depend on the organisms chosen by the student. With the alignments in hand, the students are then asked to go back to the PDB and create a figure that highlights the position of the conserved residues in the structure. For this exercise, a 10–15% sequence identity seems to be optimal. The students, therefore, are instructed to add sequences to their alignment if the proteins are related too closely or remove sequences if the percent identity falls too low. The transfer of the sequence conservation results onto a structure can be done manually but is substantially easier to accomplish with the new program ConSurf that interfaces seamlessly with PE. An example of the output from this exercise performed on PAH is shown in Fig. 3 [13]. In most cases, the exercise

shows quite dramatically a 3D clustering of conservation around the active site of the enzyme. The students then must describe the relationship between the two forms of MSA output, the primary sequence alignment file and the structural overlay. Some of the questions that can be asked to make the students think about the implications of their findings include the following.

- When you look at the primary sequence and the amino acid conservation across organisms, do you see any patterns or organization?
- Is there a relationship between the sequence conservation and the overall 3D structure?
- How would you use MSA on a nucleic acid such as a tRNA or rRNA, and what information might you obtain from such an exercise? Will you always look simply for conservation, or are there other factors that might come into play?

Project 5: Enzyme Activity Comparisons and the BRENDA Database—The final project involves analysis of kinetic data available for their unknown enzyme. These data are compiled in the BRENDA database, allowing rapid access to information on the various homologs. Here, the students must explore the reasons why kinetic data for an enzyme varies from organism to organism. Students use these data as a springboard through which they can discover the patterns evident in sequence conservation and the effect that mutations have on catalytic activity. Furthermore, they can explore the impact that experimental conditions such as pH and temperature have on the activity of a specific enzyme as they learn about how enzyme kinetics is used to decipher catalytic mechanisms.

In addition to data on the natural substrate, the database also contains entries for non-natural substrates that have been tested and various inhibitors. Students can compare the structures of the inhibitors to the natural substrates and learn about the use of transition state analogs as reversible inhibitors and suicide substrates as their irreversible cousins. The project culminates in the use of this information, together with their textbook and other literature sources, to propose a mechanism for the enzyme-catalyzed transformation in as much detail as possible.

LEARNING ASSESSMENT

Several levels of assessment must be performed to determine the efficacy of these exercises within the context of any biochemistry course. The instructions are sufficiently detailed that simply obtaining the printed output from the on-line exercise does not necessarily show understanding. Therefore, problem set questions ask the students to interpret their results, as well. These questions require the students to make judgments regarding the significance of the output and to relate the findings to other topics in the curriculum.

A broader form of assessment is used toward the end of the semester. By following the popular literature every term, a recent example from a local or national newspaper story is identified. The students are asked to find information about the underlying gene/protein by using the tools they have learned during these exercises. Here, with only minimal direction, they are asked to find specific pieces of biochemical information. This assessment tool mimics the

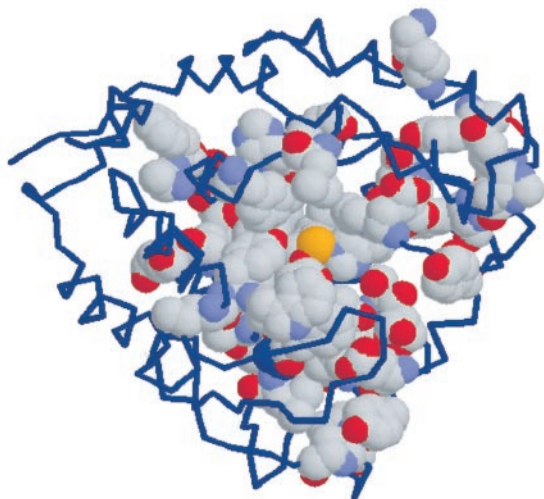
A.

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sp|P16331|PH4H_MOUSE   DVSQFLQTCTGFRLRPVAGLLSSRDFLGGLAFRVFHCTQYIRHGSKPMYTPEPDICHELL
sp|P04176|PH4H_RAT     DVSQFLQTCTGFRLRPVAGLLSSRDFLGGLAFRVFHCTQYIRHGSKPMYTPEPDICHELL
sp|P00439|PH4H_HUMAN   DVSQFLQTCTGFRLRPVAGLLSSRDFLGGLAFRVFHCTQYIRHGSKPMYTPEPDICHELL
1PAH_                   DVSQFLQTCTGFRLRPVAGLLSSRDFLGGLAFRVFHCTQYIRHGSKPMYTPEPDICHELL
sp|P17276|PH4H_DROME   DVSNFLRDCFTGFTLRPVAGLLSSRDFLAGLAFRVFHSTQYIRHPSKPMYTPEPDVCHELM
sp|P90925|PH4H_CAEEL   DVSDFLKDCTGYTIRPVAGLLSSRDFLAGLAFRVFHSTQYIRHHSAPKYTPEPDICHELL
sp|P43334|PH4H_PSEAE   EINRVLQATTGWRVARVPALIPFQTFEELLASQQFPVATFIRTPEELDYLOEPDIFHEIF
sp|P30967|PH4H_CHRVO   KLNEKLMAATGWKIVAVPLIPDDVFEHLANRRFPVTWWLREPHQLDYLOEPDVFHDLF
... *   ** :   *..*.. * : ** : * : : *
229                                     291

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B.



C.

Overall alignment statistics:

Alignment length : 468
 Identity (*) : 49 is 10.47 %
 Strongly similar (:) : 44 is 9.40 %
 Weakly similar (.) : 18 is 3.85 %
 Different : 357 is 76.28 %

FIG. 3. **Sample output from Project 4.** A, a portion of the multiple sequence alignment used for the analysis of phenylalanine hydroxylase generated by the program ClustalW. Swiss-Prot accession numbers for the sequences used in this exercise were as follows: P00439, *Homo sapiens* PAH; P04176, *Rattus norvegicus* PAH; P16331, *Mus musculus* PAH; P30967, *Chromobacterium violaceum* PAH; P43334, *Pseudomonas aeruginosa* PAH; P17276, *Drosophila melanogaster* PAH; P90925, *Caenorhabditis elegans* PAH; and 1PAH, the sequence from the crystallographic-solved PAH fragment from *Rattus Norvegicus* (13). B, structure of PAH in which the 100% conserved residues, identified through the sequence alignment in A, are shown in space-filling mode, whereas the remainder of the protein is shown as a backbone trace. C, overall statistics of the ClustalW alignment.

application of these tasks to a personal or research problem such as might be encountered beyond the realm of the classroom. A recent example derives from a report on the link between the ACC2 gene and obesity in mice, taken from a local newspaper [14], but based on a paper published in *Science* [15]. The students were required to find the full sequence of the gene and the crystal structure and perform a sequence alignment between ACC2 and ACC1, a related gene disruption of which is fatal. The students were also polled informally regarding how long it took to locate the necessary information in the databases.

Skill retention was also assessed in subsequent courses, such as the physical biochemistry course (C481), taken by the biochemistry majors. Approximately 50% students in C481 during spring 2001 had participated in these assignments during the fall term of 2000 whereas the other half had taken a more traditional biochemistry course at Indiana University or elsewhere. During the first week of the physical biochemistry course, when the instructor reviewed macromolecular structure, students with previous bioinformatics and molecular visualization experience accessed immediately the appropriate web pages and used these resources as a study aide. Students without this background were significantly more reluctant to do so,

even though they were provided with the identical PE and Chime tutorial used in the biochemistry course from the previous semester. Although anecdotal in nature, we feel quite strongly that exposure to these resources will change the perception of our students toward computer-assisted learning of biochemistry.

CONCLUSIONS

On-line data-mining tools provide students ready access to powerful tools for computational biology and biochemistry. The exercises described above can be incorporated into the biochemistry curriculum to provide students with practice performing complex computational tasks. The hands-on experience with these problems allows the students to explore a rapidly changing area of biochemistry. The conceptual tools involved in these exercises teach data analysis and critical thinking skills. These exercises also bring to life the impact that genomics and proteomics is having on the field of biochemistry. The ability to find, parse, and evaluate information from these databases will be essential for their continuing education in the field and are particularly valuable tools for students who plan to pursue careers in the laboratory sciences. The long term ramifications of these curricular changes will, of

course, require more systematic analysis of student learning and the perception students hold regarding the role technology should play in this process.

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